High-Tc Ramp-Type Josephson Junctions on MgO Substrates for Terahertz Applications

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***Abstract*—The authors successfully fabricated high-T_c ramp-type junctions with $PrBa_2Cu_{3-x}Ga_xO_{7-\delta}$ (PBCGO: x = 0.1, 0.4) barriers on MgO substrates. The junctions showed resistively shunted Josephson junction (RSJ)-like I–V curves with thermally and voltage activated conductivity. The I_cR_n products for these junctions scaled very well with the Ga-doping. Maximum response of the junctions for 100-GHz millimeter-wave irradiation could be observed up to 12 mV corresponding to 6 THz. Using far infrared laser radiation, we confirmed a terahertz (THz) response of these junctions. These results show promise for THz-wave applications of ramp-type Josephson junctions.**

***Index Terms*—Ga-doped PBCO barrier, high-temperature superconductors, MgO substrates, millimeter-wave response, ramp-type Josephson junctions, THz response.**

I. Introduction

Since the discovery of the high-temperature (high-T_c) superconductors, working above the liquid nitrogen temperature, rapid progress in the fabrication of Josephson junctions has been made. Superconducting electronics based on high-T_c Josephson junctions (HTJJ's) have several advantages, and a number of applications has been already demonstrated. One of the most promising applications lies in high-frequency detectors and generators. The maximum working frequency of HTJJ's is close to 10 THz, far infrared region (FIR) corresponding to the superconducting energy gap of high-T_c materials. Furthermore, the observed dynamic range of HTJJ's is on the order of 10^5. Moreover, we also observed direct response of grain boundary Josephson junctions (GBJJ's) on MgO and Si bicrystal substrates with 2.5-THz irradiation using a far infrared laser [1]. These results demonstrate that HTJJ's can be very relevant for terahertz (THz) applications.

The substrate choice for high-frequency applications is very important because its frequency-dependent dielectric behavior restricts the high-frequency performances of HTJJ's. Generally, substrates with low dielectric constant and low loss tangent are considered to be good candidates for high-frequency applications of HTJJ's. Among them, MgO, Al_2O_3, and $BaZrO_3$ have the lowest dielectric constants and loss tangents and show low reflectance up to 8 THz (between 8 and 27 THz these materials show high reflectance). From the literature [2]–[4] and our own investigations we conclude that these substrates are the most suitable for THz applications.

For practical THz applications, there are additional demands for the fabrication of Josephson junctions: in general, HTJJ's need to be matched to waveguide or quasi-optical input circuits with impedances of about 50 Ω. Furthermore, for high-temperature operation, the critical current of the junction has to exceed a certain value to overcome thermal noise rounding. Therefore, Josephson junctions with high I_cR_n products (I_c and R_n are the junction's critical current and normal-state resistance) are needed. Among all types of HTJJ's, ramp-type Josephson junctions were, until now, the only candidate if one required tunable junction parameters, as mentioned before. Only in this type of junction can one choose the barrier material and thickness to tune the performance. The use of $PrBa_2Cu_{3-x}Ga_xO_{7-\delta}$ (PBCGO) as a barrier material leads to high I_cR_n products and reproducible I_cR_n products. So far, I_cR_n products of 8 mV at 4.2 K have been obtained, using a 40% Ga-doped PBCGO barrier [5]. Furthermore, ramp-type junctions on yttria-stabilized zirconia substrates have shown near-millimeter response [6].

In this study, we demonstrate that it is possible to make ramp-type junctions on MgO substrates using PBCGO barriers and confirm that they can respond to THz irradiation from an FIR laser.

II. Experimental

High-T_c ramp-type Josephson junctions were fabricated on MgO(100) substrates. In this study, we used $DyBa_2Cu_3O_{7-\delta}$ (DBCO) as base and top high-T_c superconducting electrodes. To avoid the influence of a degradation layer at the MgO surface, we annealed the MgO substrates at 1100 °C in O_2 for 16 h before depositing base DBCO layers. After annealing, the MgO surface was covered with steps and terraces of several unit cells height [7]. These steps provide nucleation sites for DBCO grains, and this improves the in-plane-orientation. In-plane-orientation of the films was confirmed using an X-ray diffraction method (ϕ-scan), where it was seen that the DBCO$\langle 100\rangle$ axis is aligned with the MgO$\langle 100\rangle$ axis. As a result, we consistently obtained DBCO films with T_c of 89 K and J_c (77 K) of 3 × 10^6 A/cm^2 by off-axis rf-magnetron sputtering with an Ar + O_2 and H_2O vapor gas mixture. Optimized deposition temperatures of 740 °C for the DBCO base layers and 760 °C for the PBCGO ($x = 0.1$) isolation

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layers on MgO were usually 20–40°C lower than those on $SrTiO_3$ substrates. In the case of PBCGO barrier layers on MgO, the high-deposition temperature resulted in a very rough surface morphology for highly Ga-doped PBCGO. Thus, we used the relatively low deposition temperature of 700–720 °C for the PBCGO barrier layers.

The fabrication process of our junctions was described previously [8]. Starting from a sputtered DBCO/PBCGO ($x = 0.1$) bilayer, a ramp with an angle of ∼20° with respect to the substrate surface was etched using an Ar-ion beam. The ramp surface was subsequently ion-beam cleaned at low energy to remove damage from the interface. Next, the ramp was covered by a PBCGO ($x = 0.1$ and 0.4) barrier layer and a DBCO counterelectrode. Final junction definition, wiring, and metallization were performed by a conventional photolithographic process. The barrier thickness d for most of the junctions reported in this study was about 10 nm, as inferred from the calibrated growth rate.

I–V curves were measured with a conventional four-probe method. A magnetic field was applied perpendicular to the film by a solenoid. dV/dI curves were measured using standard low-frequency ac lock-in techniques. Microwaves (8–20 GHz) and millimeter waves (101 GHz) were generated by a synthesized signal generator and a Gunn diode and were fed to ramp-type junctions using a coaxial cable and a waveguide, respectively. Terahertz wave signals were generated by a far-infrared (FIR) laser, pumped by a 38-W CO_2 laser, yielding ∼40 mW on the 761.7-GHz formic acid line, ∼100 mW on the 1.40-THz diflorometan line, and ∼120 mW on the 2.52-THz methanol line. THz wave signals were fed to the junctions mounted on a cold stage in an infrared cryostat via a quasi-optical system consisting of a TPX lens and a hyperhemical lens made of high resistivity Si.

III. Electrical Transport Properties

It has been already reported that c-axis-oriented YBCO films grow normal to the local surface in the case of nonperovskite substrates such as yttria-stabilized zirconia and MgO [9]–[11]. We cannot neglect the possibility of generating small-angle grain boundaries in the vicinity of milled ramp surfaces using MgO substrates. If the grain boundaries have small enough critical current to show the Josephson effect, the ramp-type junctions on MgO would show I–V curves, suggesting the presence of additional weak links in series with the PBCGO weak links [9].

Fig. 1 shows a typical temperature dependence of the I–V characteristics (IVC's) for a ramp-type junction on an MgO substrate. Fig. 1(b) shows the IVC at high-bias voltages. From this, there is no evidence for additional series junctions. The observed characteristics can be very well described by the resistively shunted Josephson junction (RSJ) model. The normal resistance of the junction decreases with increasing temperature and increasing bias voltage. If the junction electrical properties were determined by grain-boundary junctions, the resistance would be independent of temperature. This indicates that the IVC's of the junctions are predominantly determined by the PBCGO barriers, instead of additional grain boundaries in the vicinity of milled ramp surface.

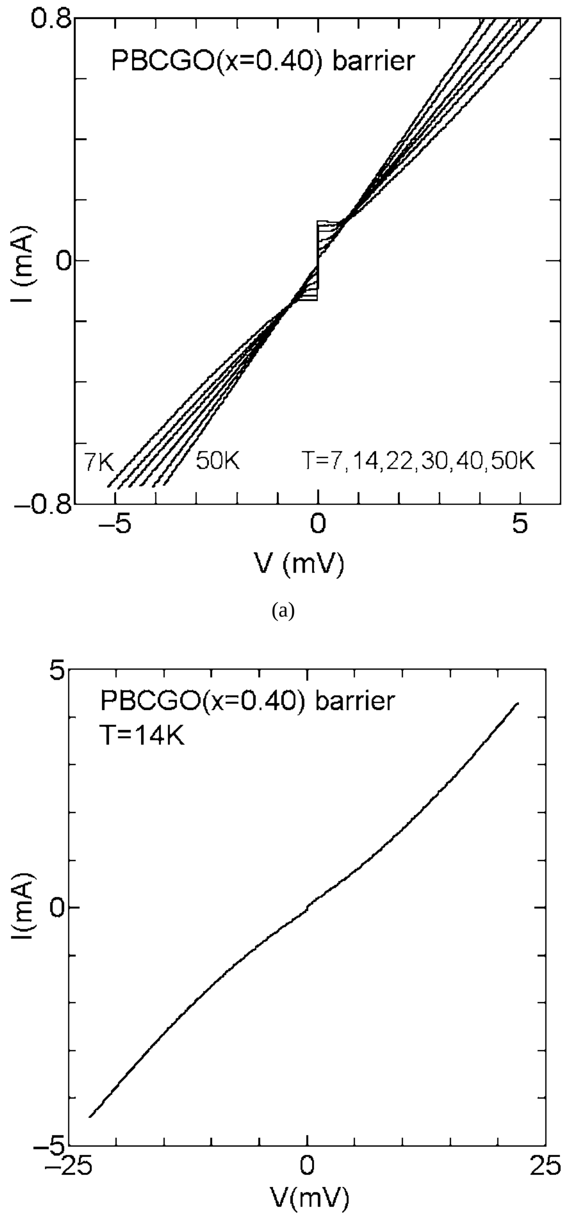


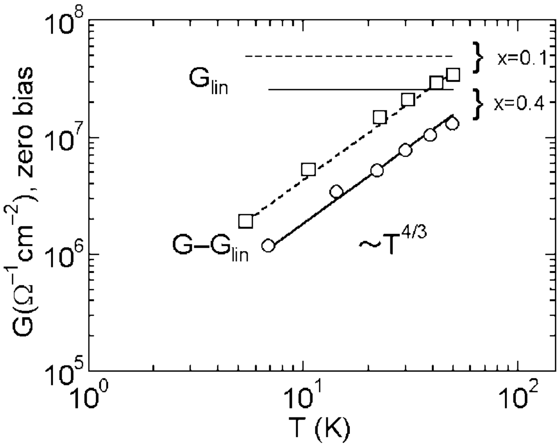
Fig. 1. Typical IVC's for a ramp-type junction with PBCGO ($x = 0.4$) barrier of 10 nm on an MgO substrate (a) at six different temperatures and (b) at high-bias voltages at 14 K.

Electric transport properties of the ramp-type junctions with PBCGO are well described by a combination of direct tunneling and resonant tunneling via n localized states (L.S.) [12]. The total conductance $G_{\rm total}$ can be written in terms of the direct tunneling component G_{div} and the resonant tunneling component $G_n(T, V)$

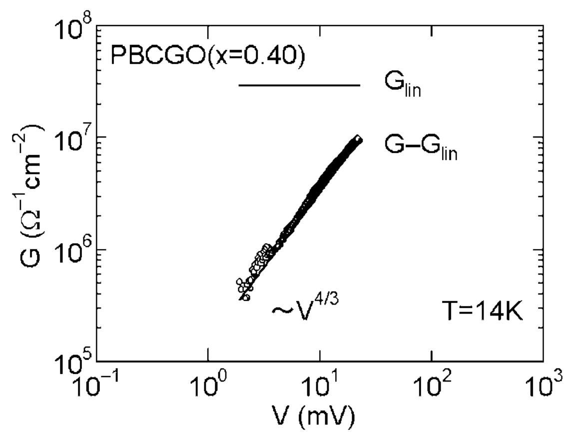
$$\begin{aligned} G_{\rm total} &= G_{\rm dir} + G_1 + G_2(T, V) + G_3(T, V) + \cdots \\ &= G_{\rm lin} + G_2(T, V) + G_3(T, V) + \cdots \end{aligned} \tag{1}$$

where $G_{\rm lin}$ is largely independent of temperature and bias voltage. Using expressions derived by Glazman and Matveev [13], two limits can be distinguished:

$$\begin{aligned} G_n(T, V) &\propto T^{n-2/(n+1)} \qquad (eV \ll k_B T) \\ G_n(T, V) &\propto V^{n-2/(n+1)} \qquad (eV \gg k_B T). \end{aligned} \tag{2}$$



(a)



(b)

Fig. 2. Dependence of activated conductivity on (a) temperature and (b) bias voltage. Horizontal lines show the extrapolated zero-temperature conductivity, representing $G_{\rm lin}$.

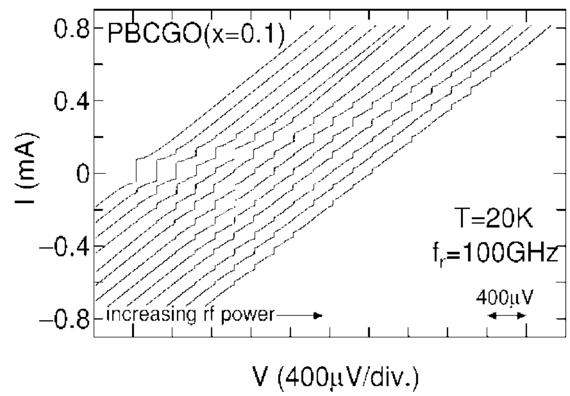


Fig. 3. I–V curves for a junction with PBCGO ($x = 0.1$) barrier under 100-GHz irradiation for 13 power levels.

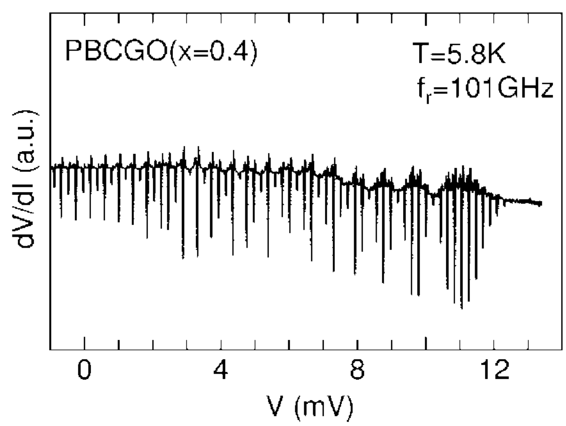


Fig. 4. dV/dI curves for a junction with PBCGO ($x = 0.4$) barrier under 100-GHz irradiation at maximum power.

Fig. 2 shows the dependence of the activated conductivity on: 1) temperature and 2) bias voltage for junctions with PBCGO barriers on MgO. These figures show $G_{\rm total} - G_{\rm lin} \propto T^{4/3}$ and $V^{4/3}$, consistent with those obtained from the junctions on $SrTiO_3$. The exponent of 4/3 corresponds to indirect passage via two localized states.

It has been reported that values of the I_cR_n product depend on the Ga-doping level, being about 1 mV for $x = 0.1$ and several mV for $x = 0.4$ for ramp-type junctions on $SrTiO_3$ with a barrier thickness of ~10 nm. For the ramp-type junctions on MgO, I_cR_n values also depend on the Ga-doping level. However, values of the I_cR_n product were several times smaller than those for the ramp-type junctions on $SrTiO_3$. One possible reason for this is that Ga atoms doped in PBCO do not eliminate localized states because of the low deposition temperature for the PBCGO barriers, compared to that on $SrTiO_3$ substrates.

IV. Response for Millimeter and THz Waves

For high-frequency applications, one needs to minimize the shunt capacitance. In the case of the $SrTiO_3$ substrates, the ramp-type junctions showed hysteretic I–V curves at low temperature. Typical capacitance per μm^2 was ~150 fF/μm^2. In the case of junctions on MgO, nonhysteretic IVC's were observed even at low temperatures. Thus, the shunt capacitances of junctions on MgO are estimated to be two orders of magnitude smaller than those on $SrTiO_3$. In the case of GBJJ's on bicrystal substrates, the capacitance of the junctions also depended on the dielectric constants of the substrates [14]. Perhaps the junction capacitance of the ramp-type junctions is predominantly determined by the stray capacitance of the substrates rather than by the capacitance of overlapping.

Fig. 3 shows I–V curves of a junction with a PBCGO ($x = 0.1$) barrier irradiated with 100-GHz millimeter wave at several powers. The power dependence of the step height is well fitted with the nth Bessel function $J_n(I_{\rm rf}/I_c)$. Under maximum irradiation power, Shapiro steps could be observed up to 12 mV without any antenna structure, as shown in Fig. 4. The maximum response voltage might be increased by using an antenna structure because maximum response was observed up to 17 mV on a GBJJ with a log-periodic antenna on a MgO bicrystal substrate. These results suggest that HTJJ's may respond up to 5–10 THz.

Using the FIR laser, it was shown that the ramp-type junctions on MgO could respond to the millimeter wave (761.7 GHz) and THz wave (1.397 and 1.627 THz). Fig. 5

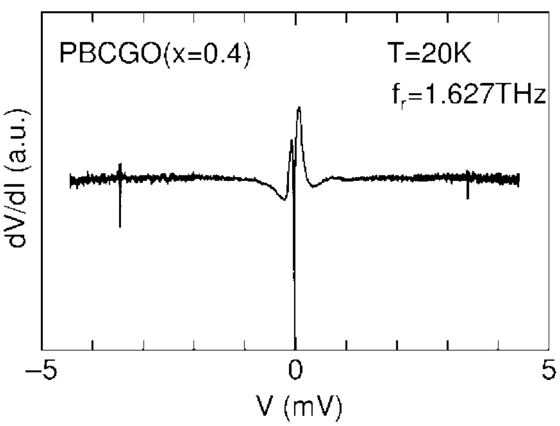


Fig. 5. dV/dI curve for a junction with PBCGO $(x = 0.4)$ barrier under 1.627-THz irradiation from an FIR laser.

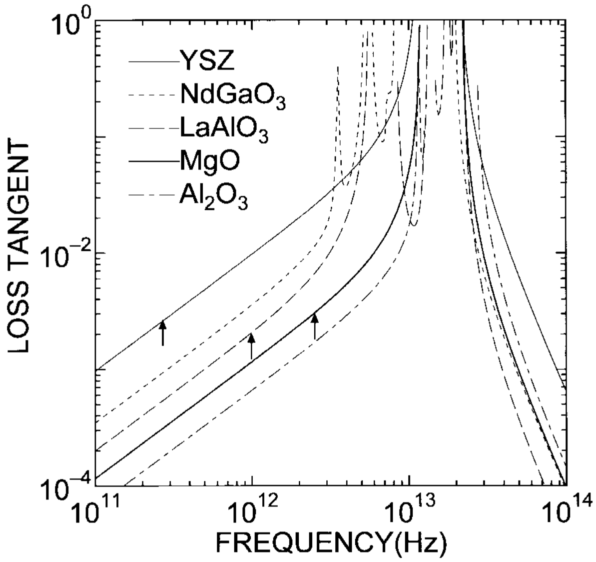


Fig. 6. Loss tangent for several substrate materials as a function of frequency, estimated from published data [2]–[4]. Three arrows show observed maximum frequencies for direct response of HTJJ's. If the loss tangent exceeds $\sim 10^2$, transmittance of the 1-mm-thick substrate is almost zero.

shows dV/dI for a junction with PBCGO $(x = 0.4)$ barrier irradiated with a 1.627-THz wave from the FIR laser. Clearly, distinct minima were observed at the expected voltages of $\pm\Phi_0 f_r \sim \pm 3.4$ mV. Very small Shapiro steps were also visible. Using the theory for the step height, we can estimate the detected power to be about 0.1 μW at the maximum. This value is six orders of magnitude smaller than the input power. Under 2.524-THz irradiation at a maximum input power of 150 mW, no response was observed. At these frequencies, the transmittance of the MgO substrate rapidly decreases because of its dielectric behavior. Fig. 6 shows the loss tangent of various substrate materials. Three arrows show observed maximum frequency for direct response of HTJJ's [1], [6], [15]. The loss tangent closely relates to the absorption of the substrates. (Actually, the loss tangent is defined by ϵ''/ϵ', where ϵ' is the real part and ϵ'' is the imaginary part of the complex dielectric function. ϵ'' is proportional to the absorptance of the substrate.) If the loss tangent exceeds $\sim 10^{-3}$, absorptance of the substrates apparently increases and irradiated power reaching to JJ's decreases. Transmittance of 1-mm-thick substrate is almost zero at the frequency region where the loss tangent exceeds $\sim 10^{-2}$, and this region contains a high reflecting region, as mentioned at the introduction. Since the arrows point to almost the same loss tangent values of 2–3 $\times$ 10^{-3}, we think that these give us the practical upper loss tangent limits for THz detection using JJ's on several substrate. Of course, there are several limitations for the high-frequency response such as reflection and absorption of irradiated signal at substrates, impedance mismatch between the antenna and JJ, and surface loss of the antenna structures. Except for optical properties of the substrates, we can eliminate limitation factors tuning up JJ impedance or using a metal antenna with low-surface losses. However, we have to use substrates to fabricate JJ's and we cannot avoid high reflection and high absorption of substrates at certain frequency regions. Since optical properties of substrates restrict the performance of THz detectors and generators in this THz region, the choice of substrate materials is very important. One possible way to improve the direct response is to use very thin substrates to minimize absorption of the input signal.

V. CONCLUSIONS

We have successfully fabricated high-T_c ramp-type junctions with PBCGO $(x = 0.1, 0.4)$ barriers on MgO substrates. The junctions showed RSJ-like I–V curves with thermally and voltage activated conductivity. The I_cR_n products for these junctions scale very well with the Ga-doping. This indicates that the I–V characteristics of the junctions are predominantly determined by the PBCGO barriers, instead of additional grain boundary junctions in the vicinity of milled ramp surface. Using FIR laser radiations, we demonstrated terahertz responses of these junctions. The junction with PBCGO $(x = 0.4)$ had I_cR_n products of $\sim$1 mV at 4.2 K and showed Shapiro steps with THz-wave irradiation, without any additional antenna structure. These results are promising terahertz applications of the ramp-type junctions.

REFERENCES

[1] K. Nakajima, J. Chen, H. Myoren, and T. Yamashita, "Terahertz response for bicrystal YBCO Josephson junctions," *IEEE Trans. Appl. Superconduct.*, vol. 7, pp. 2607–2610, 1997.
[2] D. M. Roessler and D. R. Huffman, *Handbook of Optical Constants in Solids II.* Orlando, FL: Academic, 1991, pp. 761, 919.
[3] Z. M. Zhang, B. I. Choi, M. I. Flik, and A. C. Anderson, "Infrared refractive indices of $LaAlO_3$, $LaGaO_3$, and $NdGaO_3$," *J. Opt. Soc. Am. B Opt. Phys.*, vol. 11, pp. 2252–2257, 1994.
[4] Z. M. Zhang and M. I. Flik, "Predicted absorptance of $YBa_3Cu_3O_7$/YSZ/Si multilayer structures for infrared detectors," *IEEE Trans. Appl. Superconduct.*, vol. 3, pp. 1604–1607, 1993.
[5] M. A. J. Verhoeven, G. J. Gerristima, and H. Rogalla, "Ramp type HTS Josephson junctions with PrBaCuGaO barriers," *IEEE Trans. Appl. Superconduct.*, vol. 5, pp. 2095–2098, 1995.
[6] R. Gupta, H. Qing, D. Terpstra, G. J. Gerritsma, and H. Rogalla, "Near-millimeter-wave response of high T_c ramp-type Josephson junctions," *Appl. Phys. Lett.*, vol. 62, pp. 3351–3353, 1993.
[7] T. Minamikawa, T. Suzuki, Y. Yonezawa, K. Segawa, A. Morimoto, and T. Shimizu, "Annealing temperature dependence of MgO substrates on the quality of $YBa_2Cu_3O_x$ films prepared by pulsed laser ablation," *Jpn. J. Appl. Phys.*, vol. 34, pp. 4038–4042, 1995.

[8] M. A. J. Verhoeven, G. J. Gerristima, and H. Rogalla, "Ramp-type junctions with very thin PBCO barriers," in *Proc. Eucas Conf.,* Edinburgh, U.K., 1995, pp. 1395–1398.

[9] B. D. Hunt, M. C. Foote, W. T. Pike, J. B. Barner, and R. P. Vasquez, "High-T_c edge-geometry SNS weak links on silicon-on-sapphire substrates," *Physica C*, vol. 230, pp. 141–152, 1994.

[10] J. G. Wen, N. Koshizuka, C. Traeholt, H. W. Zandbergen, E. M. C. M. Reuvekamp, and H. Rogalla, "Microstructures of ramp-edge $YBa_2Cu_3O_x$/$PrBa_2Cu_3O_x$/$YBa_2Cu_3O_x$ Josephson junctions on different substrates," *Physica C*, vol. 255, pp. 293–305, 1995.

[11] J. A. Edwards, J. S. Satchell, N. G. Chew, R. G. Humphreys, M. N. Keene, and O. D. Dosser, "$YBa_2Cu_3O_7$ thin-film step junctions on MgO substrates," *Appl. Phys. Lett.*, vol. 60, pp. 2433–2435, 1992.

[12] M. A. J. Verhoeven, G. J. Gerristima, and H. Rogalla, "Ramp-type junction parameter control by Ga doping of $PrBa_2Cu_3O_{7-\delta}$ barriers," *Appl. Phys. Lett.*, vol. 69, pp. 848–850, 1996.

[13] L. I. Glazman and K. A. Matveev, "Inelastic tunneling across thin amorphous films," *Sov. Phys. JETP*, vol. 67, pp. 1276–1282, 1988.

[14] A. Beck, A. Stenzel, O. M. Froehlich, R. Gerber, R. Gerdemann, L. Alff, B. Mayer, R. Gross, A. Marx, J. C. Villegier, and H. Moriceau, "Fabrication and superconducting transport properties of bicrystal grain boundary Josephson junctions on different substrates," *IEEE Trans. Appl. Superconduct.*, vol. 5, pp. 2192–2195, 1995.

[15] P. A. Rosenthal and E. N. Grossman, "Terahertz Shapiro steps in high temperature SNS Josephson junctions," *IEEE Trans. Microwave Theory Tech.,* vol. 42, pp. 707–714, 1994.

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Horst Rogella (M'88), photograph and biography not available at the time of publication.